BIOMORPHIC ROBOTIC SYSTEMS & THEIR MISSION APPLICATIONS

Sarita Thakoor

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109-8099
Ph: (818)354-3991
e-mail: sarita.thakoor@jpl.nasa.gov

Presentation: The International Conference for Smart Systems and Robotics in Space and Medicine
September 6-8, 2000, Houston, Texas

BIOMORPHIC EXPLORERS

- **A MULTIDISCIPLINERY SYSTEM CONCEPT FOR SMALL, DEDICATED, LOW-COST EXPLORERS THAT CAPTURE SOME OF THE KEY FEATURES OF BIOLOGICAL ORGANISMS**
  - **Small... 100-1000g (useful space/terrestrial exploration functions are implementable* using this mass)**
- **CONDUCTED WORKSHOP, AUG 19-20, 1998**
  - **SPONSORED BY NASA/JPL**
  - **WEBSITE: http:/nmp.jpl.nasa.gov/bees/** CL 99-668
  - **AN ENTHUSIASTIC RESPONSE: OVER 150 PARTICIPANTS**

* JPL DOCUMENT D-14879A, JPL DOCUMENT D-16300A, JPL DOCUMENT D-16500, AUTHOR: SARITA THAKOOR

sarita.thakoor@jpl.nasa.gov

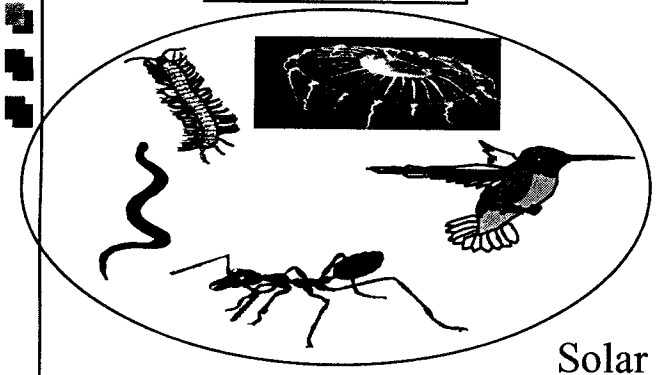
THE CHALLENGE TO OBTAIN A BIOMORPHIC ROBOT

- NATURE'S CREATIONS
  - PRIMARILY ORGANICS BASED
  - EVOLUTION LED SURVIVING DESIGN AND MINIMALIST OPERATIONAL PRINCIPLES ARE INHERENT
  - GEOLOGICAL TIME SCALE HAS BEEN USED FOR EVOLUTION
- BIOMORPHIC ROBOT
  - PRIMARILY INORGANICS BASED, THE INGREDIENTS/MATERIALS AVAILABLE TO US
  - NEEDS TO BE CREATED BY DISTILLING THE PRINCIPLES OFFERED BY NATURAL MECHANISMS. CAPTURING THE BIOMECHATRONIC DESIGNS AND MINIMALIST OPERATION PRINCIPLES FROM NATURE'S SUCCESS STRATEGIES
  - DO IT WITHIN A LIFETIME

sarita.thakoor@jpl.nasa.gov

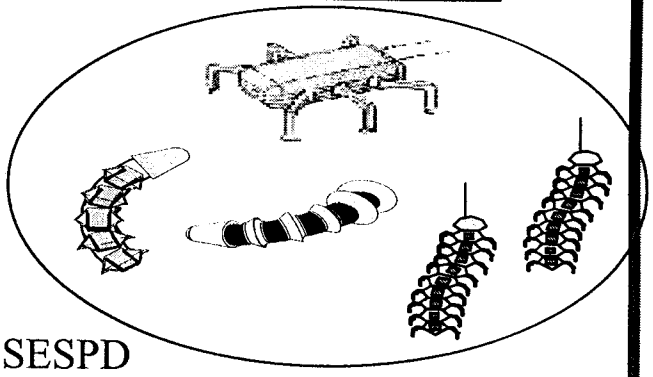
1st NASA/JPL WORKSHOP ON BIOMORPHIC EXPLORERS FOR FUTURE MISSIONS

INSPIRATION

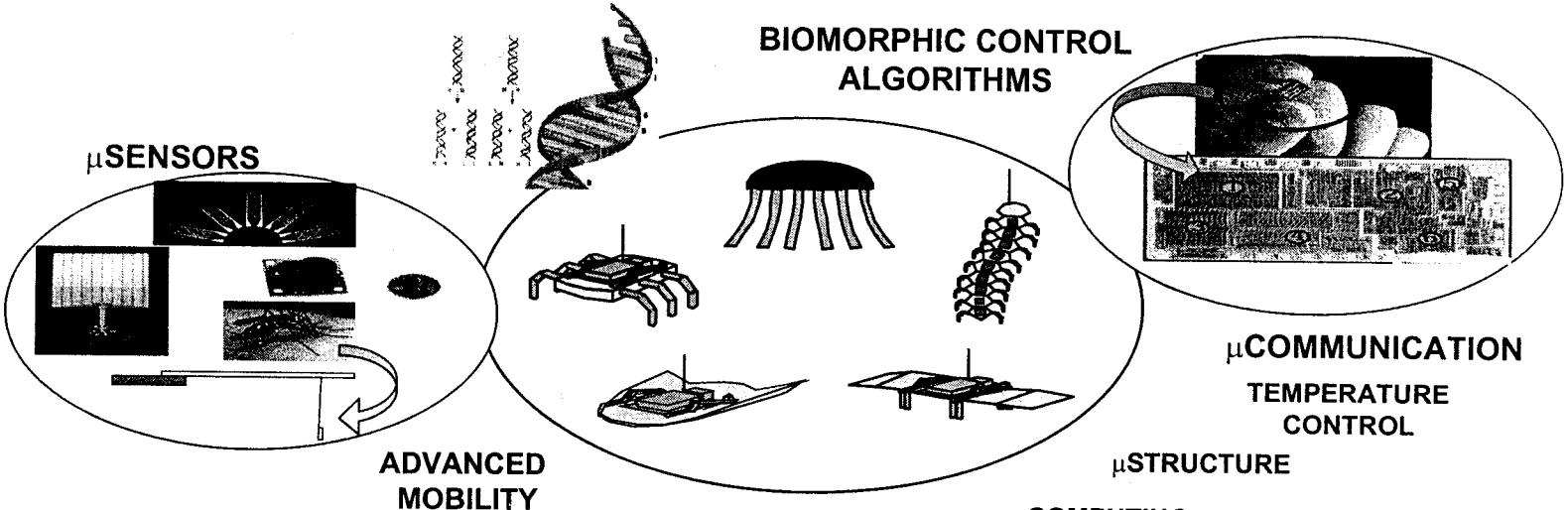


August 19 - 20, 1998
Jet Propulsion Laboratory
Pasadena, CA
Auditorium 180 - 101

IMPLEMENTATION

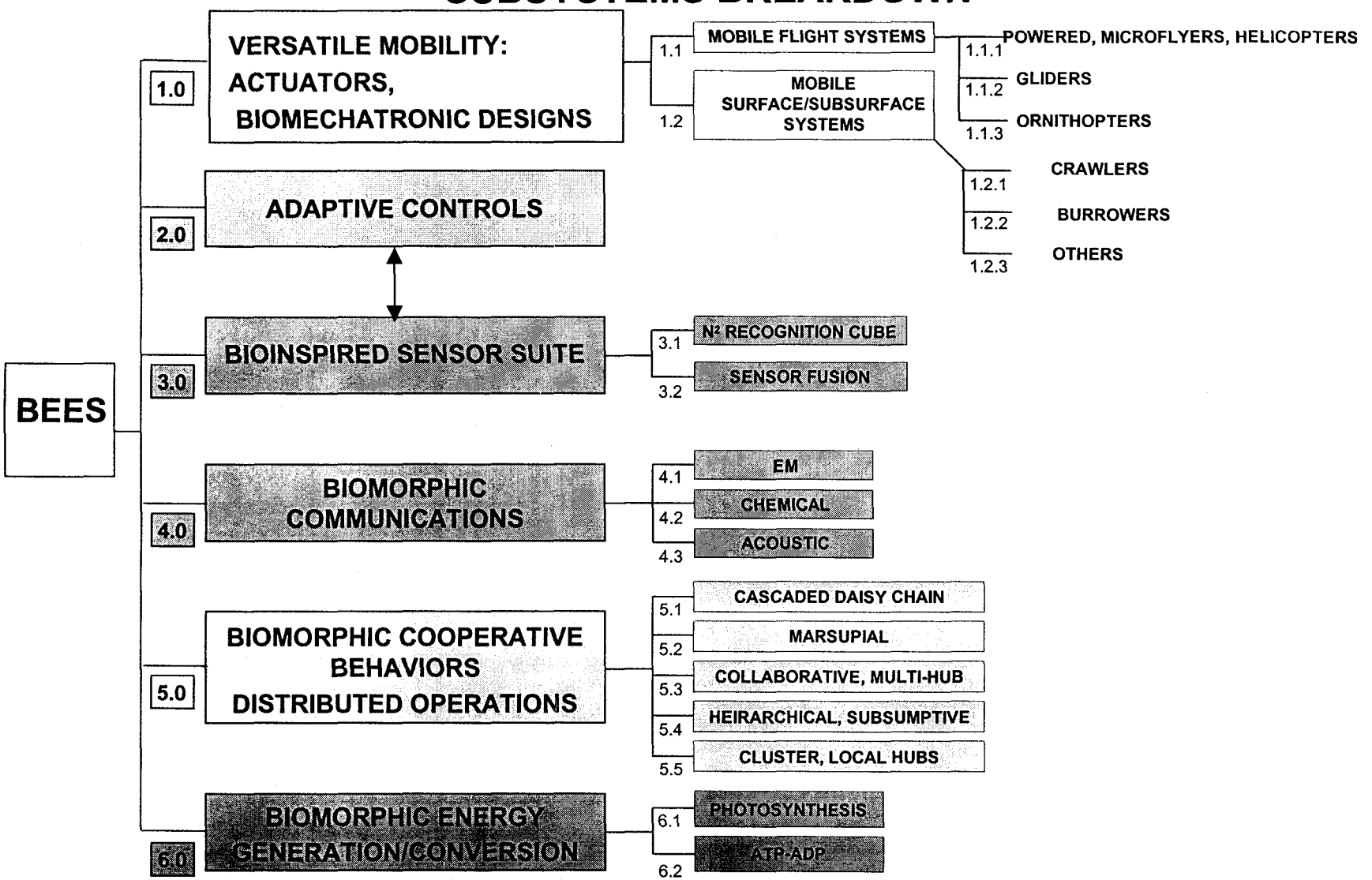


Sponsored by NASA/JPL
Solar System Exploration Program, SESPD
New Millennium Program, NMP
Space Mission Technology Development Program, TAP
Center for Integrated Space Microsystems, CISM



TECHNICAL POC: SARITA THAKOOR
sarita.thakoor@jpl.nasa.gov

BIOINSPIRED ENGINEERING OF EXPLORATION SYSTEMS (BEES) SUBSYSTEMS BREAKDOWN



sarita.thakoor@jpl.nasa.gov

Biomorphic Explorers: Classification
(Based on Mobility and Ambient Environment)

Biomorphic Explorers

Aerial

Biomorphic Flight Systems

Surface/Subsurface

Biomorphic Surface Systems

Biomorphic Subsurface Systems

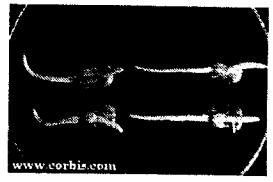
Seed Wing

Monarch Butterfly

Ant

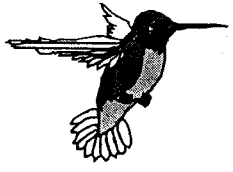
Centipede

Earthworm



Germinating Seed

Soaring Bird



Humming Bird

Inchworm

Snake

Examples of biological systems that serve as inspiration for designing the biomorphic explorers are illustrated. Pick a feature, say soaring, the intent is to make a explorer that combines the different attributes seen in nature in diverse species and capture them all in one artificial entity, in that sense the explorer goes beyond biology to provide us the adaptability that we need in encountering and exploring what's as yet unknown

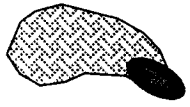
sarita.thakoor@jpl.nasa.gov

Biomorphic Explorers: Classification (Based on Mobility and Ambient Environment)

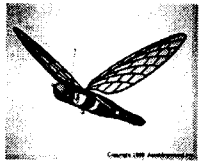
Biomorphic Explorers

Aerial

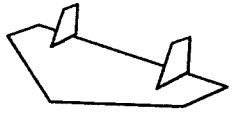
Biomorphic Flight Systems



Seed Wing Flyer (60 g)



Ornithopter



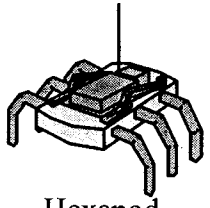
Glider (100 g - 2000g)

AeroVironment

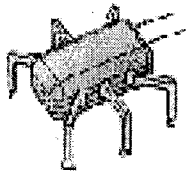
Powered Flyer

Surface/Subsurface

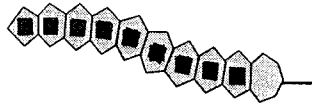
Biomorphic Surface Systems



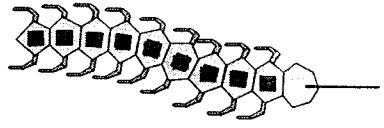
Hexapod (1-2 kg)



Reconfigurable Legs/Feet



Biomorphic Subsurface Systems



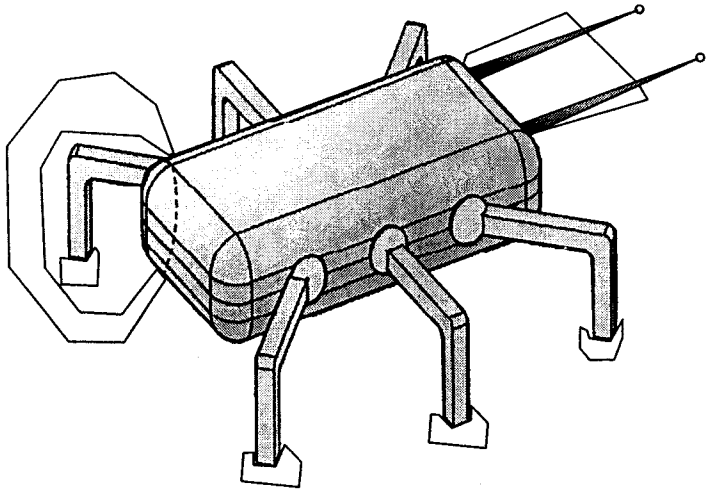
Artificial Earthworm

Worm Robot

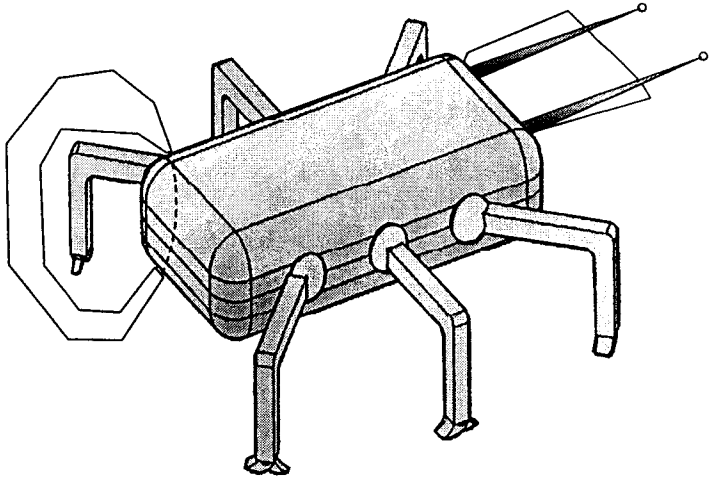
Candidate biomorphic explorers on the drawing board, with mass of design under study in parentheses

sarita.thakoor@jpl.nasa.gov

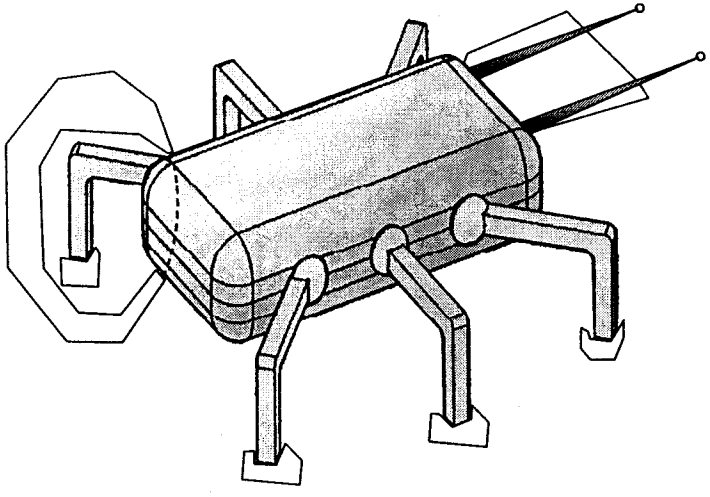
MULTITERRAIN RECONFIGURABLE LEGGED EXPLORER



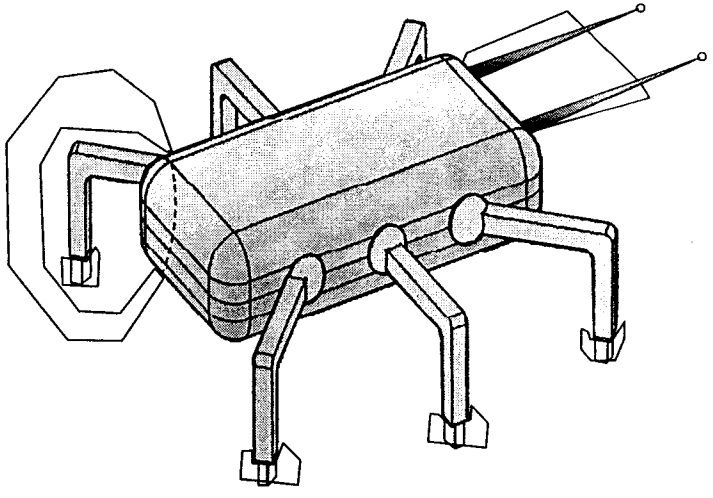
NARROW FOOTPRINT



WIDE FOOTPRINT



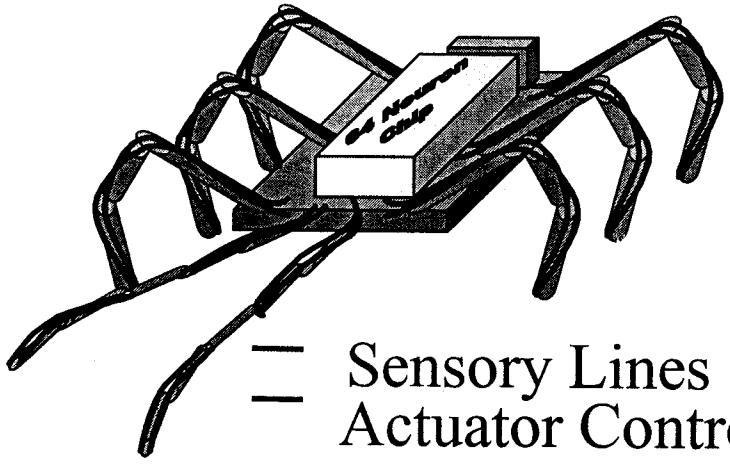
SHORT LEG



LONG LEG

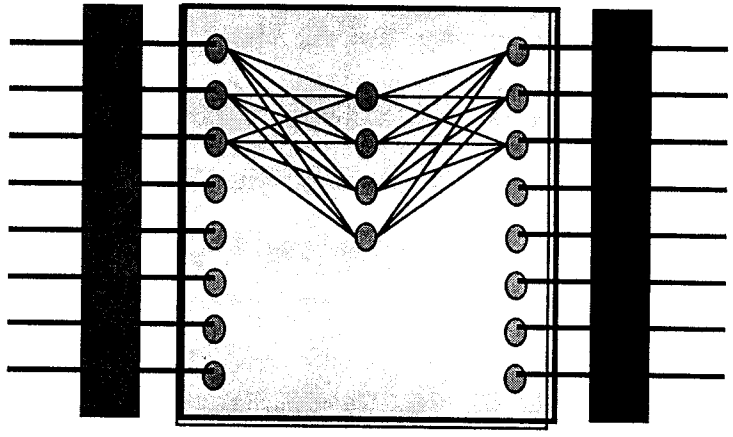
sarita.thakoor@jpl.nasa.gov

MULTITERRAIN Biomorphic Explorer



— Sensory Lines
— Actuator Controls

Neural connections mapped on 64 Neural Network (NN) Chip

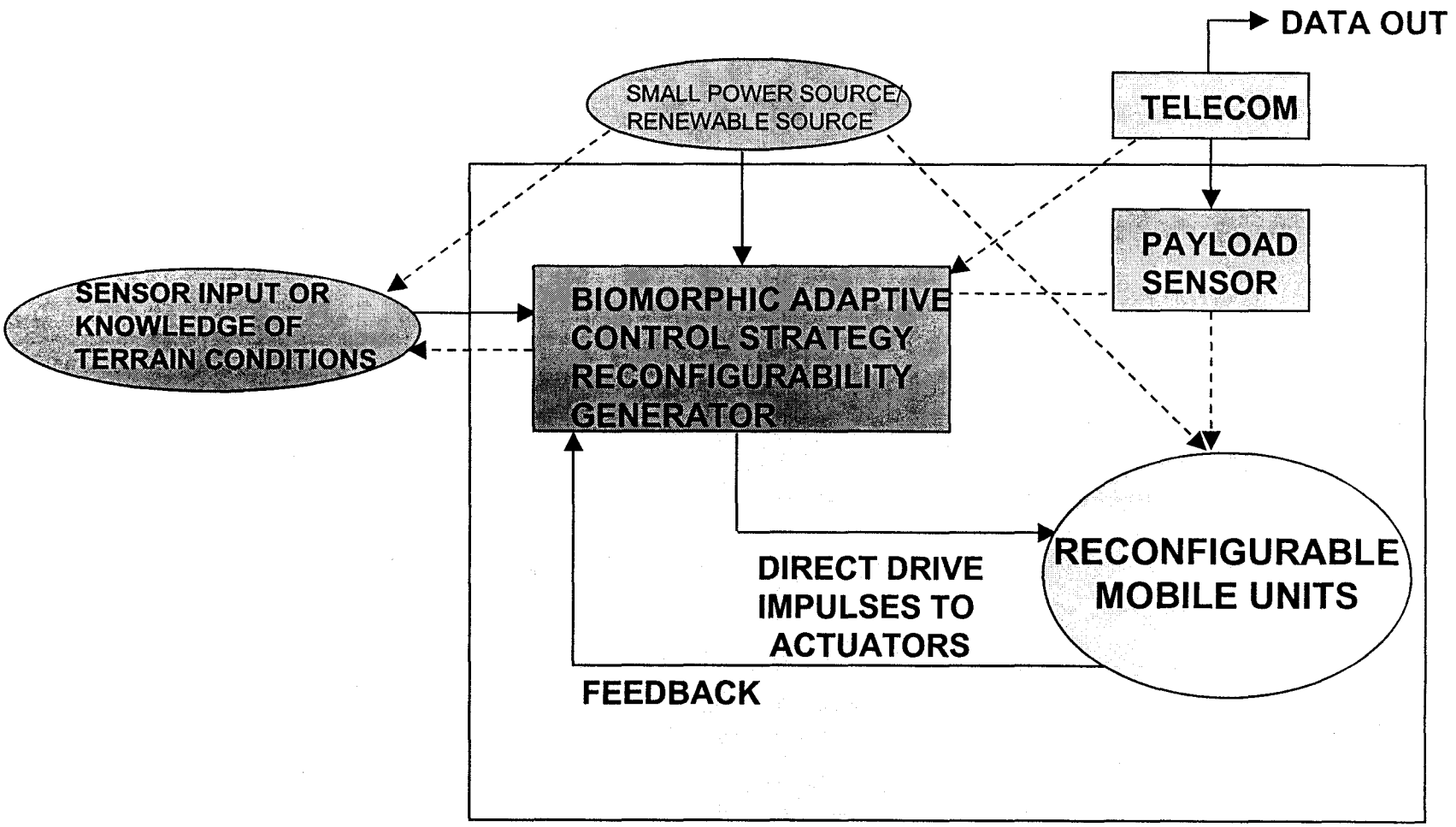


JPL's 64 NN chip characteristics:

- Low Weight (5 g)
- Small Size (1 cm x 1 cm)
- Low Power (12 mW)
- High Speed (~250 ns)
- Programmable Neural Network Architecture

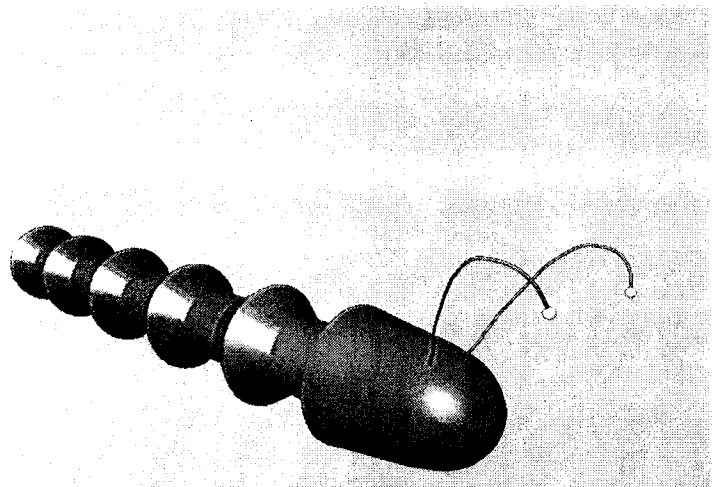
sarita.thakoor@jpl.nasa.gov

Distributed Control Operational Schematic

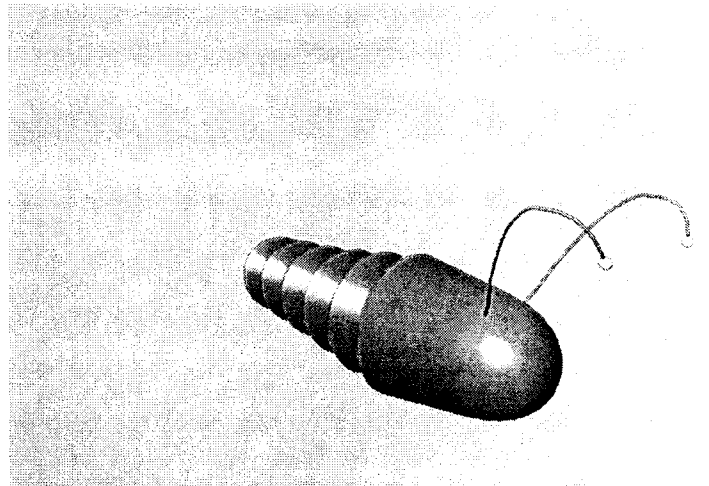


sarita.thakoor@jpl.nasa.gov

WORM ROBOT FOR IN-SITU EXPLORATION



EXTENDED CONFIGURATION



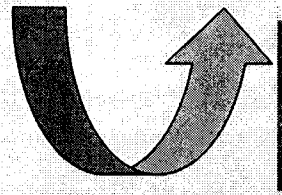
CONTRACTED CONFIGURATION

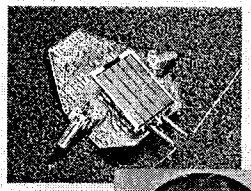
*Z. Gorjian and S. Thakoor, "Biomorphic Explorers Animation Video", 1st NASA/JPL WORKSHOP ON BIOMORPHIC EXPLORERS FOR FUTURE MISSIONS, August 19-20, 1998; Jet Propulsion Laboratory, Pasadena, CA

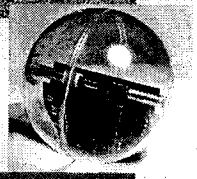
sarita.thakoor@jpl.nasa.gov

BIOMORPHIC EXPLORERS: VERSATILE MOBILITY

BIOLOGICAL EXAMPLE OF RECONFIGURABLE MOBILE UNIT

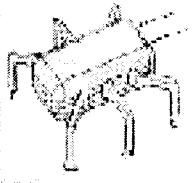






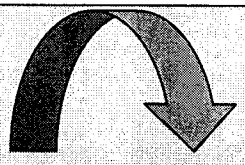
Solorbotics

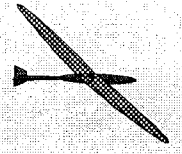
Xerox

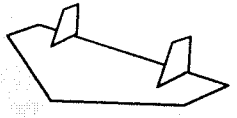


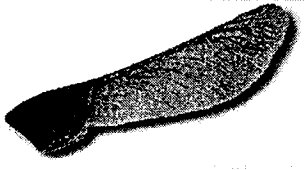
CHALLENGE: TO DESIGN RECONFIGURABLE MOBILE UNIT

SURFACE/ SUBSURFACE

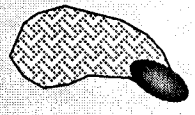








BIOLOGICAL EXAMPLES OF FLYERS



BIOMORPHIC FLIGHT SYSTEMS
• DOD LEVERAGE

FLYERS

sarita.thakoor@jpl.nasa.gov

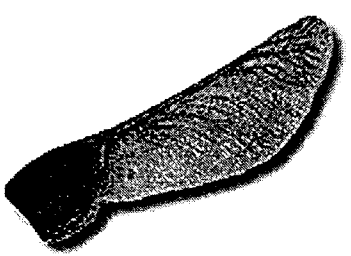
Biomorphic Flight Systems

- Extended reach over all kinds of terrain
- Unique perspective for IMAGING, SPECTRAL SIGNATURE, ATMOSPHERIC MEASUREMENTS
- Deploy/Distribute Payloads
- Many biomorphic explorers(seedwing flyers, crawlers, burrowers, gliders etc) work in cooperation with larger UXV'S to enable new missions and achieve successfully currently UNATTAINABLE MISSIONS

sarita.thakoor@jpl.nasa.gov

Plant world inspired payload distribution methods

- **Simpler and smaller than parachute on small scale for dispersion of sensors and small surveillance instruments.**
- **Controlled Descent Rate ~ 15 m/s (on surface of Mars)**



(a)

Maple Seed Samara

(b)

Dandelions

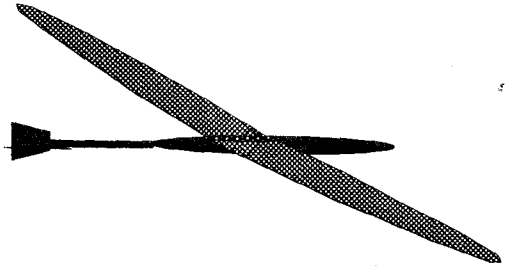
Design Goals:

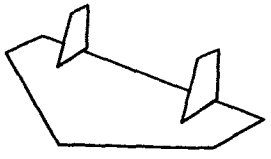
- Small total mass, ~100 g
- High payload mass fraction, > 80%
- Captures key features of controlled and stable descent as observed in Samaras, such as maple seeds
- Reliable, minimal infrastructure
- unobstructed view overhead for atmospheric measurements
- simple construction, few constituent parts

sarita.thakoor@jpl.nasa.gov

Biomorphic Gliders

- Small, simple, low-cost system ideal for distributed measurements, reconnaissance and wide-area dispersion of sensors and small experiments.
- Payload mass fraction 50% or higher.





- small mass (100 g - 1000 g)
- low radar cross section
- larger numbers for given payload due to low mass
- precision targeting to destination
- amenable to cooperative behaviors
- missions use potential energy: deploy from existing craft at high altitude
- Captures features of soaring birds, utilizing rising currents in the environment
- *Adaptive Behavior*
- *Self Repair features*

sarita.thakoor@jpl.nasa.gov

BIOMORPHIC EXPLORERS

- Bio-morphic explorers constitute a new paradigm in mobile systems that capture key features and mobility attributes of biological systems, to enable new scientific endeavors.
- The general premise of biomorphic systems is to distill the principles offered by natural mechanisms to obtain the selected features/functional traits and capture the biomechatronic designs and minimalist operation principles from nature's success strategies.
- Bio-morphic explorers are a unique combination of versatile mobility controlled by adaptive, fault tolerant biomorphic algorithms to autonomously match with the changing ambient/terrain conditions.
- Significant scientific payoff at a low cost is realizable by using the potential of a large number of such cooperatively operating biomorphic systems.
- Biomorphic explorers can empower the human to obtain extended reach and sensory acquisition capability from locations otherwise hazardous/inaccessible

sarita.thakoor@jpl.nasa.gov

BIOMORPHIC MISSIONS

•Biomorphic Missions are co-operative missions that make synergistic use of existing/ conventional surface and aerial assets along with biomorphic robots.

•Just as in nature, biological systems offer a proof of concept of symbiotic co-existence, the intent here is to capture/imbibe some of the key principles/success strategies utilized by nature and capture them in our biomorphic mission implementations.

•Specific science objectives targeted for these missions include

- close-up imaging for identifying hazards and slopes,
- assessing sample return potential of target geological sites,
- atmospheric information gathering by distributed multiple site measurements, and
- deployment of surface payloads such as instruments/biomorphic surface systems or surface experiments.

sarita.thakoor@jpl.nasa.gov

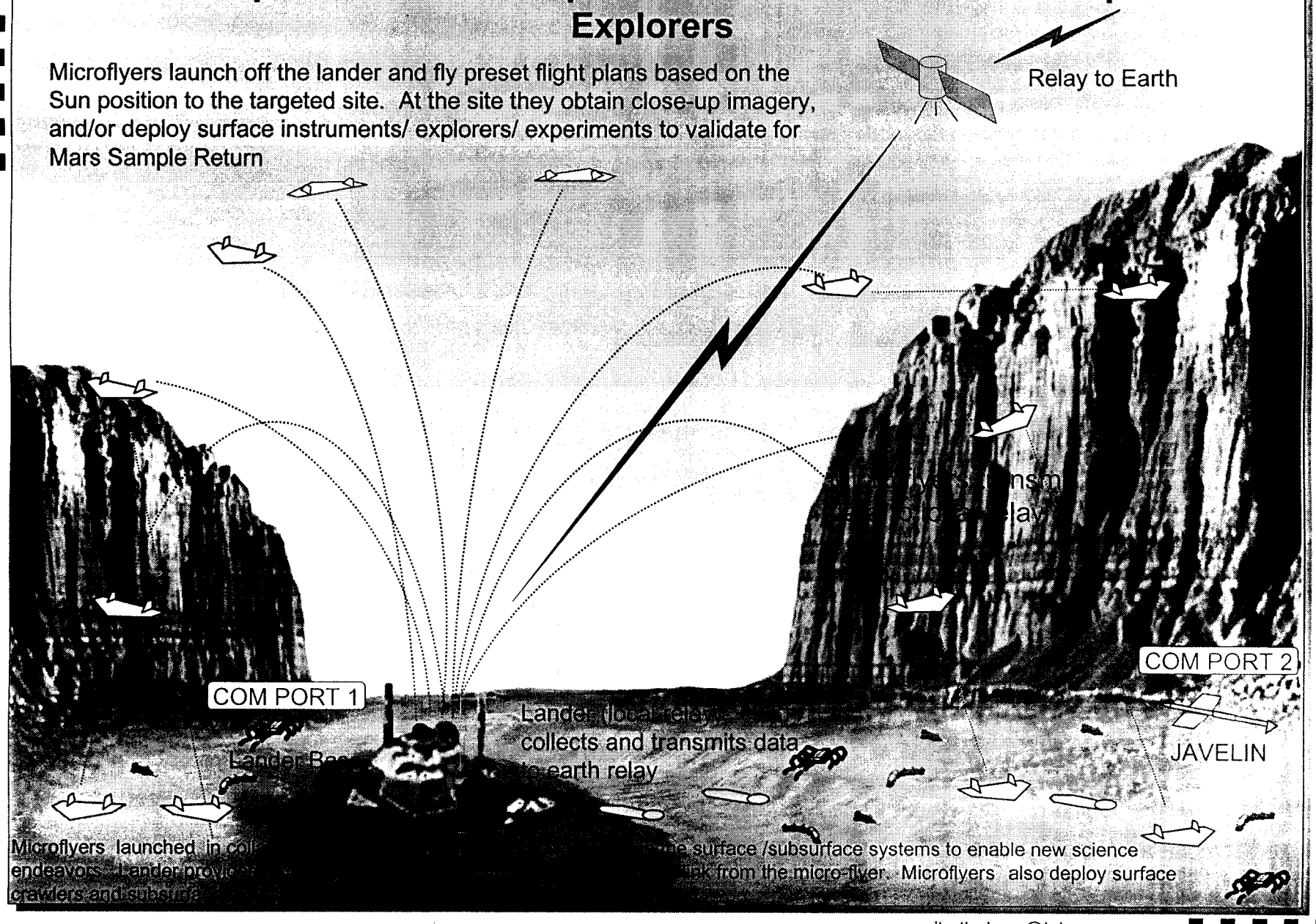
Science Requirements

- Orbiter provides imaging perspective from ~ 700 Km height with resolution ~ 1.5 m/pixel; lander mast imagery is view from ~ 1-2 m height, the essential mid range 50m-1000m altitude perspective is as yet uncovered and is an essential science need. Imaging from this mid-range is required to obtain details of surface features/topography, particularly to identify hazards and slopes for a successful mission)
  - Close-up imagery of sites of interest (~ 5 - 10 cm resolution)
  - 1-10 Km range, wide area coverage
  - Distributed Measurements across the entire range
  - In-situ surface mineralogy.
- Candidate instruments include
  - Camera (hazard & slope identification by close-up imagery)
  - Meteorological suite (in-flight atmospheric measurements)
  - Microphone to hear surface sounds, wind and particle impact noises
  - Electrical Measurement of surface conductivity
  - Accelerometer Measurement of surface hardness
  - Seismic measurement (accelerometers)

sarita.thakoor@jpl.nasa.gov

Biomorphic Mission: Cooperative Lander/Rover - Biomorphic Explorers

Microflyers launch off the lander and fly preset flight plans based on the Sun position to the targeted site. At the site they obtain close-up imagery, and/or deploy surface instruments/ explorers/ experiments to validate for Mars Sample Return



sarita.thakoor@jpl.nasa.gov

BIOMORPHIC EXPLORERS

- An auxiliary payload of a Mars Lander (2-10kg)
- Micro-gliders (4 - 20) launched/deployed from the Lander
- Lander serves as a local relay for imagery/data downlink
- Micro-Glider provides :
  - Close-up imagery of sites of interest (~ 5-10 cm resolution)
  - Deploys Surface payload/experiments (20g - 500 g)
  - In-flight Atmospheric Measurements
  - Candidate instruments
    - Camera (hazard & slope identification by close-up imagery)
    - Meteorological suite (in-flight atmospheric measurements)
    - Microphone to hear surface sounds, wind and particle impact noises
    - Electrical Measurement of surface conductivity
    - Accelerometer Measurement of surface hardness
    - Seismic measurement (accelerometers)

- 50m-500m height, unique and essential perspective for imaging
  - 1-10 Km range, wide area coverage very quickly
  - useful close-up imagery and surface payload deployment
- 2003/2005 Missions - Scout Missions, Sample Return Missions 2007 and beyond

sarita.thakoor@jpl.nasa.gov

Surface Launched Mars Microflyers: Applications

- Contamination Free Launch options
  - •Spring launched (massive, KE left over, complex possibly damaging recoil)
  - •Electric launch options (power hungry)
    - •electrically driven propeller (Mars atmosphere too thin)
    - •electromagnetic gun
  - •Inflate and release a balloon (complicated mechanism, thin atmosphere a challenge, susceptible to winds
  - •Pneumatic, compressed gas launch (simple mechanism, simple recoil, leading candidate)
- Rocket Boosted launch (contaminants, HCl, nitrates etc.) a good option for application such as scouting where contamination is not an issue

sarita.thakoor@jpl.nasa.gov

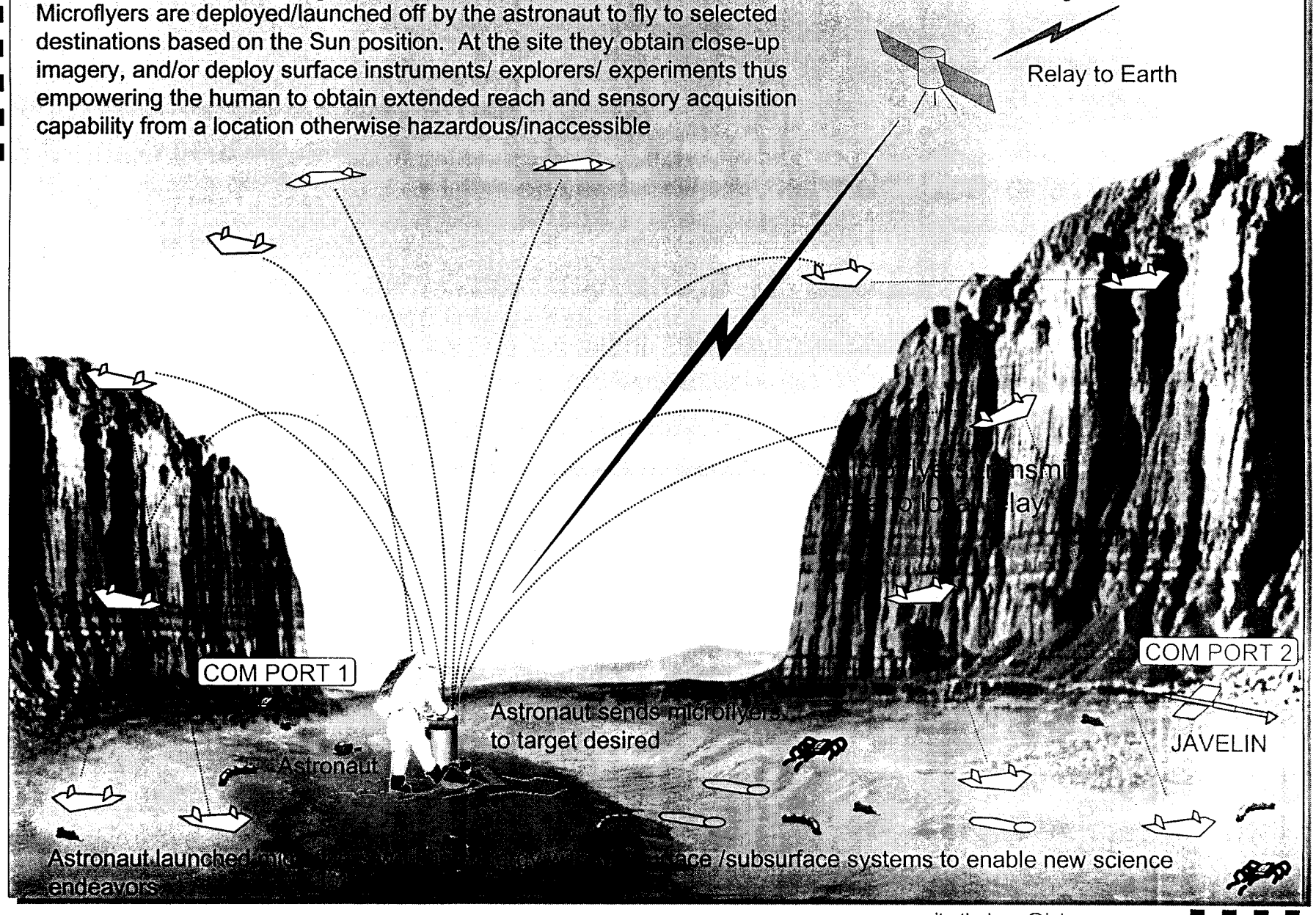
Science Objectives:

- Near Term 2003/2005
  - Image surface topography
  - Characterize terrain around lander
  - Identify rocks of interest for rover
  - Distribution of Instruments/Experiments/Surface explorers to targeted sites
- 2005 - 2007
  - Identify and collect sample enabling sample return
- Long Term 2007 and beyond
  - Co-operative Operation of a multitude of Explorers together to obtain imagery, and deploy surface payloads
  - Astronaut Launched Microflyers: empowering the human to obtain extended reach and sensory acquisition capability from locations otherwise hazardous/inaccessible

sarita.thakoor@jpl.nasa.gov

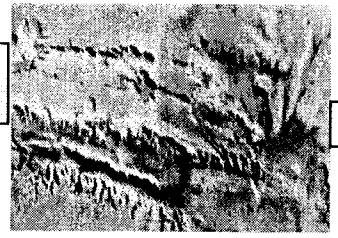
Biomorphic Mission: Astronaut Launched Micro-Flyers

Microflyers are deployed/launched off by the astronaut to fly to selected destinations based on the Sun position. At the site they obtain close-up imagery, and/or deploy surface instruments/ explorers/ experiments thus empowering the human to obtain extended reach and sensory acquisition capability from a location otherwise hazardous/inaccessible



sarita.thakoor@jpl.nasa.gov

Enabling Processor for Surface Feature Recognition



SURFACE FEATURE RECOGNITION

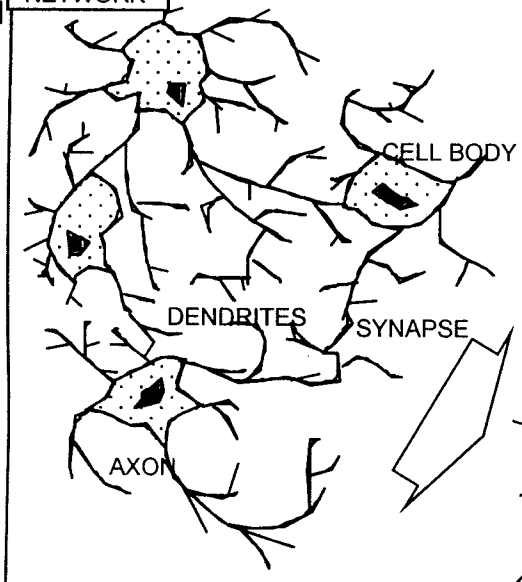
FEATURE LIBRARY

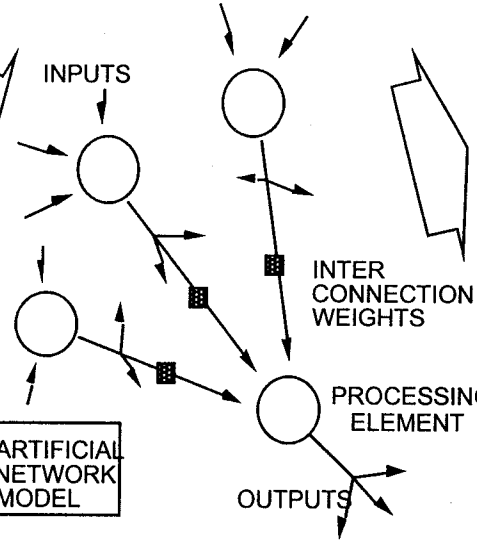
BIOLOGICAL NEURAL NETWORK

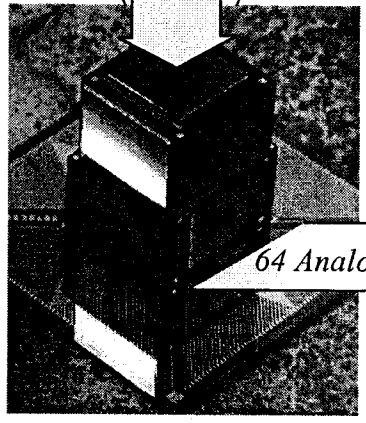
TOPOGRAPHY MAP

Input to

3D Artificial Neural Network (3DANN)







64 Analog Outputs

Identified Feature

10 gm, 5 cc, 2 W

On-chip IR detector

1 trillion 8-bit multiplies/sec

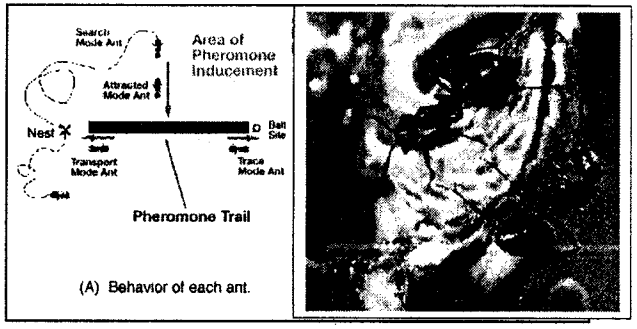
270 million template matches/sec

Compute power greater than fast supercomputer

JPL neural network chip design enables the 3DANN technology that delivers unprecedented processing speed for ATR: ***(64 convolutions of 64x64 masks in 16 msec vs. 2 hours on state-of-the-art workstations)***

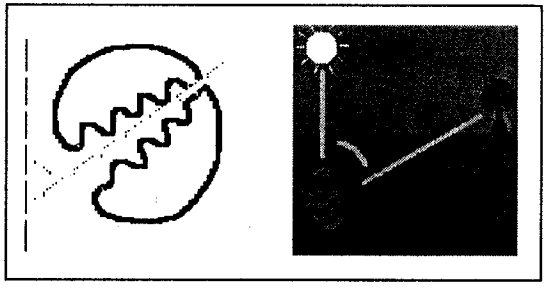
sarita.thakoor@jpl.nasa.gov

Insects operating cooperatively :



Nakamura and Kurumatani, 1995
Kubo, 1996

Ants' elaborate communication method with pheromone trails



Karl von Frisch, 1965
Wehner and Rossel, 1985
Barbara Shipman, 1997

Honeybee's recruitment dance with the sun as a celestial reference

sarita.thakoor@jpl.nasa.gov

SCIENCE APPLICATIONS

- **CLOSE-UP IMAGING, EXOBIOLOGY SITE SELECTIONATMOSPHERIC INFO GATHERING**
- **DISTRIBUTED MULTIPLE SITE MEASUREMENTS**
- **DEPLOY PAYLOAD: INSTRUMENTS/CRAWLERS**
- **SAMPLE RETURN RECONNAISSANCE**
- **EXTEND THE SENSORY ACQUISITION CAPABILITY OF THE ASTRONAUT**

sarita.thakoor@jpl.nasa.gov

SCIENCE APPLICATIONS

....WHICH WOULD BE ENABLED/ENHANCED BY SUCH EXPLORERS.....

- VALLES MARINERIS EXPLORATION
  - ONE SINGLE SITE RICH IN GEOLOGIC UNITS
  - STUDY STRATIGRAPHIC COLUMN TOP TO BOTTOM ALONG THE CANYON WALL
  - OPTIMUM SCIENCE SAMPLE SITE

  ....imager, temperature sensor, pressure sensor, sniffer: e-nose, individual gases, elements, etc.

- SCOUTING FOR CONDITIONS COMPATIBLE WITH LIFE TO LEAD US TO THE SPOTS THAT MAY HOLD SAMPLES OF EXTINCT/EXTANT LIFE
  - WIDE-AREA SEARCH WITH INEXPENSIVE EXPLORERS EXECUTING DEDICATED SENSING FUNCTIONS

  ....Individual gases, sniffer: e-nose, chemical reactions, pyrotechnic test, elements, specific amino acids, signatures of prebiotic chemistry, etc.

- GEOLOGICAL DATA GATHERING:
  - DISTRIBUTED TEMPERATURE SENSING
  - SEISMIC ACTIVITY MONITORING
  - VOLCANIC SITE

  ....Multitude of explorers working in a cascade or daisy-chain fashion cooperatively to fulfill task

sarita.thakoor@jpl.nasa.gov

Applications (Dual Use NASA & DoD)

- Distributed Aerial Measurements
  - Ephemeral Phenomena
  - Extended Duration using Soaring
- Delivery and lateral distribution of Agents (sensors, surface/subsurface crawlers, clean-up agents
- Close-up Imaging, Site Selection
  - Meteorological Events: storm watch
  - Reconnaissance
  - Biological Chemical Warfare
  - Search and Rescue etc
  - Surveillance
  - Jamming

sarita.thakoor@jpl.nasa.gov

BIOMORPHIC EXPLORERS

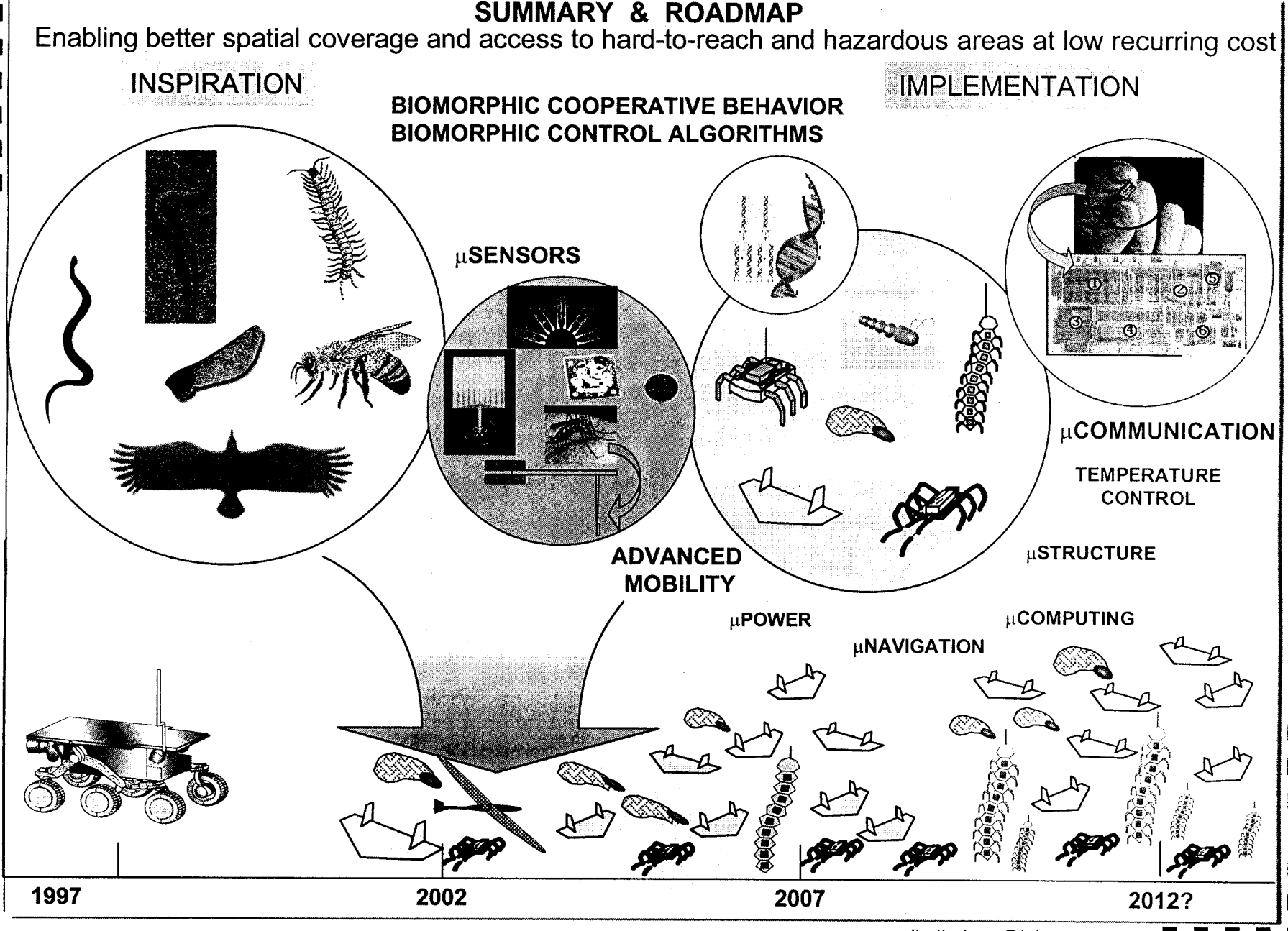
- **PAYOFF**

- **BIOMORPHIC EXPLORERS, IN COOPERATION WITH CURRENT EXPLORATION PLATFORMS CAN ENABLE**
  - **EXPLORATION OF CURRENTLY INACCESSIBLE AND/OR HAZARDOUS LOCATIONS**
  - **MUCH BROADER COVERAGE OF EXPLORATION SITES**
  - **EXPLORATION AT LOWER COST**

sarita.thakoor@jpl.nasa.gov

SUMMARY & ROADMAP

Enabling better spatial coverage and access to hard-to-reach and hazardous areas at low recurring cost



sarita.thakoor@jpl.nasa.gov

ACKNOWLEDGMENTS

The research described in this document was carried out by the Jet Propulsion Laboratory (JPL), California Institute of Technology, under a contract with the National Aeronautics and Space Administration (NASA).

JET PROPULSION LABORATORY

INDUSTRY: RAYTHEON, AEROVIRONMENT, SONY, XEROX, PIONEER

NATIONAL LABS: LANL, SRI, ORNL, SANDIA

ACADEMIA: MINNESOTA, BERKELEY, CALTECH, PENN STATE, VANDERBILT, USC, UCLA, ARIZONA, ROCHESTER, MONTANA, CORNELL, NAGOYA, JAPAN

OTHER NASA CENTERS:GSFC, AMES, LANGLEY, JSC

sarita.thakoor@jpl.nasa.gov

Acknowledgements

JPL

Brett Kennedy/Terry Huntsberger: Mechanical Design & Control
John Michael Morookian: Electrical design and system Integration
Gerhard Klose: Structure
Ken Klassen/T.Cunningham: Camera
Anil Thakoor: Image Processing
Dave Bell (& CALTECH): Telecom
Terry Martin: Atmospheric Science
Frank Palluconi: Science Imagery
Satish Krishnan/Robert Manning: Lander/Rover

sarita.thakoor@jpl.nasa.gov